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Future of Inertial Fusion Energy

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FUTURE OF INERTIAL FUSION ENERGY

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Abstract

In the past 50 years, fusion R&D programs have made enormous technical progress. Projected billion-dollar scale research facilities are designed to approach net energy production. In this century, scientific and engineering progress must continue until the economics of fusion power plants improves sufficiently to win large scale private funding in competition with fission and non-nuclear energy systems. This economic advantage must be sustained: trillion dollar investments will be required to build enough fusion power plants to generate ten percent of the world's energy.

For Inertial Fusion Energy, multi-billion dollar driver costs must be reduced by up to an order of magnitude, to a small fraction of the total cost of the power plant. Major cost reductions could be achieved via substantial improvements in target performance—both higher gain and reduced ignition energy. Large target performance improvements may be feasible through a combination of design innovations, e.g., "fast ignition," propagation down density gradients, and compression of fusion fuel with a combination of driver and chemical energy. The assumptions that limit projected performance of fusion targets should be carefully examined. The National Ignition Facility will enable development and testing of revolutionary targets designed to make possible economically competitive fusion power plants.

The potential for major improvements in target performance is implied by four considerations: the fast ignitor scheme[1], the large inefficiencies in current designs, the experimentally-untested assumptions which limit estimates of target performance, and the lack of an experimental facility to test novel ideas. The objective of this analysis is to search for promising new approaches

The two-driver fast ignitor scheme is a promising approach to increasing target performance. However, there is a serious problem: as the driver energy is reduced, the target gain must increase. If the driver requirement is reduced to a hundred kilojoules, then the target gain must be increased to 5,000 in order to generate the 500 MJ fusion yields required for commercial scale power plants (1 GWe, 5Hz, 40% thermal-electric efficiency).

This gain problem can be solved by developing target designs to meet the conflicting driver requirements on DT density. Since mass times density squared is a constant at fusion criticality (defined by a density-radius product), the ignition driver energy is minimized with high density DT. Since the Fermi energy increases with the two-thirds power of density, the compression driver energy is minimized with low density DT. Also, fusion depletion effects may be reduced with lower density DT.

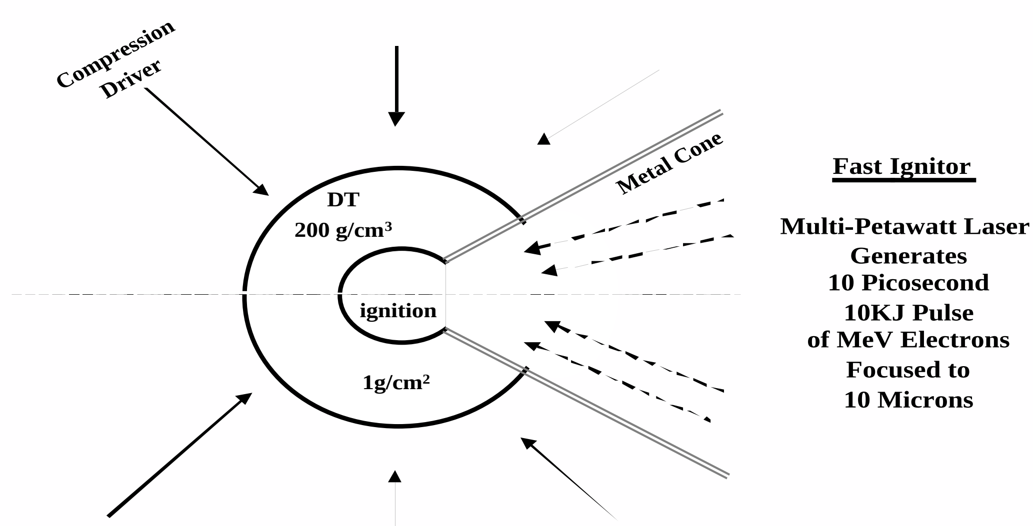
Very high gains may be achieved if the TN burn can be propagated from a minimum mass of high density DT (ignited by a fast ignitor laser) into a much larger mass of low density DT compressed in a driver-energized, non-ablative implosion. Maximum gains may be achieved by propagating the TN burn into DT non-ablatively compressed to a few g/cm^3 with a combination of driver and chemical energy, i.e. an exothermal propellant.

This analysis is organized into four sections:

1. Fast Ignitor scheme;
2. TN propagation to lower density DT;
3. Non-ablative Implosions and Exothermal Propellants;
4. Role of NIF in Developing High Performance Targets.

Section 1. Fast Ignitor Scheme

A 10-100 TW compression driver near isentropically compresses DT to densities of ~200 g/cm^3. A multi-petawatt "fast ignitor" laser then ignites the compressed DT. A 1-10 ps laser pulse is focused to intensities of ~10^{20} w/cm^2, generating a multi-MeV electron beam which penetrates into the dense DT and heats 0.3 g/cm^2 to ~10 KeV ignition temperatures. The laser may also be focused into a hollow cone to reach the dense DT core.



Fast Ignitor Target with Cone

Fig. 1

Fusion reactions rapidly self-heat the DT to higher temperatures and thermonuclear burn propagates radially outward igniting all of the dense DT. (If a smaller DT mass with a density higher than 200 g/cm^3 can be ignited, the required fast ignitor driver energy is reduced. If a lower density region is ignited, the fast driver energy is increased.)

The performance advantage of the fast ignitor scheme can be estimated by comparing the required implosion velocities, 1.4 x 10^7 cm/s to compress DT isentropically to 200 g/cm^3, and 4 x 10^7 cm/s to isentropically compress the dense shell in the alternative target to more than 1,000 g/cm^3 and ignite the ~70 g/cm^3 hot core. (The core and shell are roughly isobaric at stagnation.) The ratio of the square of these velocities is ~10. Hence, the fast ignitor scheme may reduce the compression driver energy requirement by up to ten fold. However, the performance advantage is reduced because two drivers are used. The implosion stability requirement is relaxed (because of the smaller implosion velocity), and the symmetry requirement is relaxed because there is no central hot bubble requiring a high convergence ratio.

Can two drivers be cheaper than one driver? For IFE power plant fusion yields ($\geq$500 MJ), the compression driver energy requirement is estimated to be up to ten times larger than that of the ignition driver. If the coupling of the ignition driver to the target is comparable to that of the compression driver, and if its cost per joule is comparable to the cost of the compression driver, the two-driver approach can in principle, reduce overall driver costs. However, the fast ignitor driver cost is uncertain.
There are also major uncertainties in the coupling efficiency. It has not been determined experimentally, and the physics is so complex that theoretical estimates have large uncertainties. The coupling efficiency is probably less than 10%. At ultra-high intensities, the laser absorption is probably less than 50%. Less than 50% of the absorbed laser energy is likely to generate multi-MeV electrons (energy also goes to fast ions, plasma turbulence and super high magnetic fields). Less than 50% of the multi-MeV electrons have an energy for which the range is not too short or too long in the ignition region of dense DT. It is unlikely that more than 50% of the electrons will be aimed into the 30-micron diameter ignition region (corresponding to a density-radius product of 0.3 g/cm^2 for 200 g/cm^3 DT), and roughly half the energy is deposited in a collision between an MeV electron and a cold electron. The coupling efficiency may be increased if the ultra-strong magnetic fields which are generated by enormous electron currents act to confine the energetic electrons. (These large magnetic fields may also relax DT ignition conditions.)

A similar chain of less then 50% factors is involved in coupling estimates of low Z ion beams generated by fast ignitor lasers.

The version of the fast ignitor target with a metal cone (into which the intense laser beam is focused) may have a higher coupling efficiency because the laser/electron beam need not transport through low-density plasma ablated from the target. However, high Z material mixed from the high density metal cone into the DT may degrade the yield and make ignition more difficult.

A fast ignitor coupling efficiency of 5% ± a factor of two is a good guess based on our present state of ignorance. Five percent will be assumed here.

A compression driver-target coupling efficiency of 5% is also assumed for ablative implosions. Alpha (α), the figure of merit of the isentropic compression, is assumed to be ~ one. In practice, α's less than 1.5 are difficult to achieve, so that in effect, the assumed compression coupling efficiency is 7 $\frac{1}{2}$%. The ablative coupling efficiency is degraded by a large factor because the driver beam heats all of the material which has previously been ablated, and the expanding material velocity is too high relative to the implosion velocity.

Using the Fermi density and DT burn efficiency equations, it is estimated that almost a MJ of driver energy would be required to compress enough DT to 200 g/cm^3 to generate a 500 MJ yield. If reaction chamber effects reduce the rep rate to 1 Hz, or if a large 5 GWe, 5 Hz power plant is assumed in order to reduce the ratio of driver cost to reactor cost, then a 2.5 GJ TN yield would be needed, and a compression driver energy of several MJ would be required. The corresponding target gain is ~ 800.

How can the gain can be increased by propagating the TN burn from the 200 g/cm^3 DT into large masses of much lower density DT? And how can the 5% coupling efficiency inherent in ablative implosions be substantially increased?

Section 2. TN Propagation To Lower Density DT

Assume a spherical, uniform density ignition region and a concentric region with a much smaller density. (A density gradient is approximated by a density step.) Each region has a density radius product of ~1 g/cm^2 so that a burn efficiency of ~12% is achieved in both regions. The design condition is that enough fusion alpha particle energy is generated in the dense ignited region to heat 0.3 g/cm^2 of the adjacent lower density region to 10 KeV, so as to ignite this region. This design condition determines the maximum density reduction and mass increase in the adjacent region.

A 1 g/cm^2 DT explosion generates ~ 40 x 10^9 J per gram of fusion energy. Twenty percent of this energy (8 x 10^9 J/g) is transported and deposited by 3.5 MeV α particles, and approximately 90% of the 14 MeV neutron energy escapes. The total deposited energy is ~ 10 x 10^9 J/g. In propagation, roughly half the energy is kinetic and half is thermal (5 x 10^9 J/g). Heating DT to 10 KeV requires 10^9 J/g. Consequently, the ignition mass plus up to 4 times more mass can be heated to 10 KeV (depending on the spatial distribution of the thermal energy). The inner 0.3 g/cm^2 of a 1 g/cm^2 sphere contains $(0.3)^3$ of the mass. The mass ratio of adjacent regions is $4x(0.3)^{-3}$ ~ 140. Since $M\rho^2$ is constant (ρR is 1 in both regions), the density ratio is $\leq \sqrt{\ }$ 140, or 12 fold. LASNEX calculations are required to improve this rough estimate. To be conservative, a density ratio of 8 and a mass ratio of 64 are assumed to approximate a density gradient which can sustain TN propagation.

Simple scaling is determined by the energy equation for Fermi degenerate DT. In 8x lower density isentropically compressed DT, the specific compressional energy is reduced by 4 fold ($8^{2/3}$). Hence, 16X more compressional energy is used to compress 64 times more mass. Since the burn efficiency of both regions is equal, the yield is increased 64-fold, and the gain is increased almost 4-fold relative to the ignitor gain.

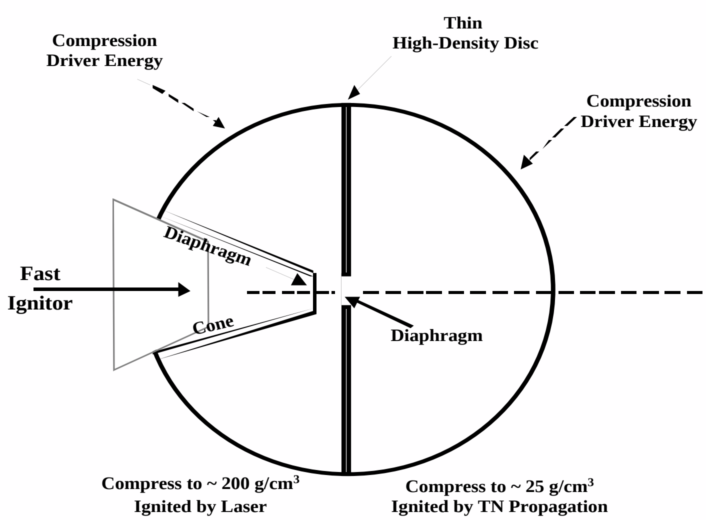
Compare the performance of a 200 g/cm^2 uniform density target to that of an 8-fold less dense 25 g/cm^3 target. In the higher density target, the compression energy/g is higher by 4-fold. Hence, for the same compression driver energy, the fuel mass is reduced 4-fold. But the density radius product is increased by $(M\rho^2)^{1/3}$ or ~ 2.5 fold. Correcting for DT depletion effects the burn efficiency increases by ~ 2 fold. Therefore, the lower density target has a 2-fold higher yield. If this 25 g/cm^3 region in turn ignites a 64 times more massive, eight-fold less dense region (~ 3 g/cm^3), the gain may be increased four-fold.

However, compensating effects must be addressed in the implosion process. In isentropically imploded targets with a large internal pressure gradient at stagnation, it is implied that not all the imploding matter has stagnated simultaneously, so that significant energy inefficiencies may exist in the implosion. Then, the advantage gained by propagating into lower density may be reduced or lost, depending on the target design.

Consider a simple spherical target design in which two concentric shells of solid DT fuel are separated by DT gas. Velocity multiplication of ~50% may occur in the implosion when the more massive outer shell collides with the inner shell. If the more massive shell has $(1.5)^2$ less kinetic energy/g, it will compress to less than $\frac{1}{3}$ the density. Simultaneous stagnation will not be achieved and the compression efficiency will be reduced. LASNEX calculations are required to determine any increase in target performance when this design is optimized.

A key question: for spherical targets, does an initial density distribution exist in combination with a special pulse shape such that a near optimum compressed density distribution can be achieved with high efficiency? The answer may be yes, but LASNEX calculations are required to confirm this conjecture. More complex designs may have higher gain, including non-uniformly imploded spherical targets, and partitioned targets, e.g., a sphere divided into hemispheres by a thin high-density metal disc.

One hemisphere of a partitioned sphere may be compressed to 200 g/cm^3 and ~1 g/cm^2 with ~ 20 KJ of compression driver energy, and ignited by a 100 KJ fast ignitor laser. The other hemisphere may be compressed with $\leq$ 200 KJ of driver energy to 25 g/cm^3.



"Hemispheres" Target

Fig. 2

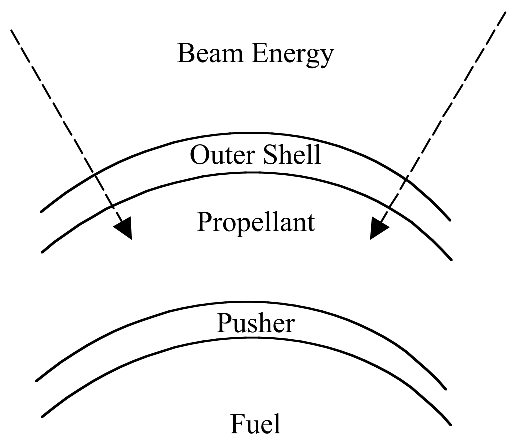
The two hemispherical implosions may be synchronized by starting the two sides at slightly different times, levitation of one hemisphere, use of different driver beam intensities, and by other means. Upon simultaneous stagnation of the two hemispheres and ignition of one hemisphere by the fast ignitor beam, the adjacent lower density hemisphere may be ignited by propagation with energy from TN neutrons, a shock generated by the heated/accelerated disc, and 3.5 MeV α_particles and hot plasma transported through a hole located at the center of the thin disc which separates the two hemispheres. As in the fast ignitor cone, the hole contains a diaphragm thin enough to be transparent to 3.5 MeV alphas ($\leq$0.1 g/cm^2).

Excessive mixing of the disc material into the DT would make ignition more difficult, and reduce the target gain. LASNEX calculations are required.

To achieve a fusion yield of 500 MJ with 100 KJ of compression driver energy, the coupling efficiency to the low density hemisphere may be increased by use of a non-ablative implosion or the burn may be propagated to an even lower density region non-ablatively imploded with an exothermal propellant.

Section 3.   <u>Non-ablative Implosion and Exothermal Propellants</u>

The coupling efficiency may be increased to more than 25 % if most of the heated material which drives the implosion can be prevented from escaping outward during the implosion by use of a dense outer shell – in effect creating a cannon instead of an isothermal rocket.



Non-Ablative Implosion

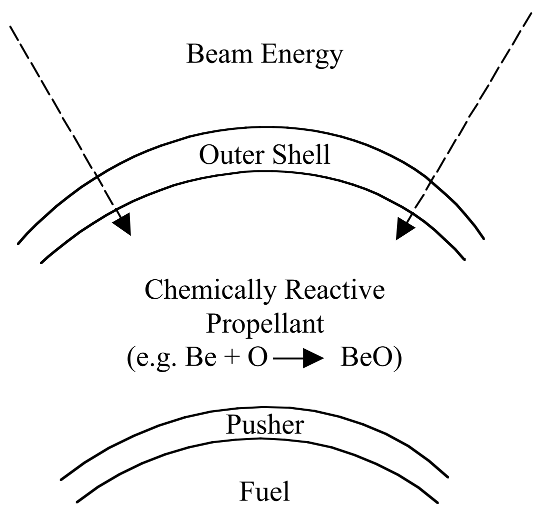
Fig. 3

However, pulse shaping will be very limited, ablative stabilization mechanisms will be lost, and symmetry and stability may be significantly degraded if the confined propellant is not heated relatively uniformly (e.g., by an ion beam, which penetrates the outer shell and heats the propellant, or by multiple laser pulses injected through holes). The non-ablative approach is not suitable for the high velocity, pulse shaped, highly symmetric, ablatively stabilized, high gain ICF targets. But for low velocity implosions of DT to 3 g/cm^3 or 25 g/cm^3, without a requirement to generate ignition temperatures, the non-ablative approach may be advantageous because of the several-fold higher coupling efficiency.

To reduce the required implosion velocity, a dense high Z pusher is introduced, with a mass ~ ten times as large as that of the DT. This pusher also enables near isentropic compression to be achieved without pulse shaping in an impulsively accelerated system. During TN burn, this shell retards the outward expansion increasing the burn efficiency. The required ignition temperature is reduced because loss of bremstrahling radiation is reduced and more time is available for fusion bootstrapping.

Using a non-ablatively imploded hemispherical pusher to compress DT to 25 g/cm^3, which is then ignited by propagation from the 200 g/cm^3 fast-ignited hemisphere, it appears to be feasible to generate 500 MJ with a hundred kilojoule fast-ignitor laser and a hundred kilojoule compression driver. LASNEX calculations are required to improve this estimate.

In implosion systems which compress DT to 3 g/cm^3 the required driving pressure approaches a megabar. At this energy density, an exothermal propellant may be useful, i.e., the driver heated propellant undergoes exothermal chemical reactions.



Exothermal Propellant

Fig. 4

More than $2x10^4$ joules per gram may be generated by the fast reaction of hot sub-micron-size particles of Be or B mixed with a suitable oxidizer.

In current approaches, drivers are 5% efficient in coupling to the DT, each driver is ~10% efficient, and the power plant which energizes the driver is ~ 40% efficient. The combination of these factors gives an overall efficiency of ~ 2×10^{-3}. It is 10-100 times more energy efficient to compress DT with chemical energy generated in the propellant than to use chemical energy to fuel electrical power plants which energize drivers which heat ablators which compress DT.

Section 4. <u>Role of NIF in Development of High Performance Targets</u>

With a greater than one hundred kilojoule, multi-petawatt capability and a two megajoule compression energy capability, NIF would have the necessary energy, power and flexibility (in pulse shaping, focusing geometry, etc.) to achieve ignition, and to test high performance target designs.

Because of the complexity and non-linearity of the associated physics, the first successful experiment is necessarily large-scale and ultra-conservative in order to avoid/limit chaotic instabilities and multiple known/unknown failure modes. After the initial success, progress can be made by following a “chain of successes” strategy—a stepwise series of successful experiments leading to the performance limits. At each step, ideas are experimentally tested, local stability limits are probed, limited/controlled or avoided by modifying and testing a series of target designs.

Some performance improvements may be foreseeable. Others are not. There are high performance target concepts, and serious difficulties, which we don’t yet understand.

In pursuing a chain of successes strategy with NIF, the current design assumptions which seem to limit performance can be tested. Many may be bypassed by novel target designs. These assumptions concern:

- drivers
- stagnation conditions (e.g. isobaric vs. gradients)
- stability limits (e.g. in-flight aspect ratio, super strength materials)
- sphericity
- ablative vs. non-ablative implosions
- magnetic fields – imposed and self-generated

Outlook for IFE

If the fast ignitor and related high performance targets are successful, the outlook for IFE will be strengthened. If the fast ignitor is impractical, and alternatives cannot be invented, IFE may focus entirely on larger than one GWe scale systems. High-performance targets will be required, but with gains less than 1000. For example, consider a “reactor park” with five 2 GWe power plants all driven by a 25 Hz 2MJ time shared Heavy Ion Accelerator costing two billion dollars (10% of the estimated 20 billion dollar cost of the reactor farm). The required fusion yield for 40% efficient power plants would be 1,000 MJ. The corresponding target gain is then 500. Major target innovations would be required to achieve these high gains.

Reducing driver costs by inventing higher performance targets is necessary but not sufficient for the commercial success of IFE. It is also necessary to create a significant economic advantage. Advanced targets which burn D_2 fuels may contribute to such an advantage by making possible an increase in the thermal-electric efficiency.

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[1] Michael H. Key, "Fast Track to Fusion Energy,” *Nature* **412**, 775-776 (2001).